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# OJ 287 and the predicted fade of 1998*

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**Abstract.** There were predictions that blazar OJ 287 should have faded in late 1997 or early 1998. The observational background for these predictions is the sudden fade of OJ 287 in 1989. Back then, the radio flux decreased steadily for 4–5 months and then the brightness dropped also in the optical region suddenly for 2–3 weeks to all time low values, e.g. V=17.4 mag. The predictions are based on a binary black hole model, where the companion black hole and its accretion disk eclipse the emission areas of the primary black hole. We have made observations of OJ 287 during the time of the predicted fade. The results show that, in the optical, OJ 287 starts to fade almost linearly in December 1997 until mid-February 1998, when it suddenly shows a sharp rise and sharp fade, and starts to get brighter again. The radio observations show no signs of variability, but the radio flux has been very low since the 1995 outburst. We also have earlier observations since Fall 1993 to Spring 1998, which show that the local minimum reached in February 1998 was the lowest since 1995. We have made observations with several telescopes in the optical (UBVRI) and radio (22 and 37 GHz) bands. We discuss the various events in the light curves and their implications on the proposed models, especially the binary black hole model by Lehto & Valtonen (1996), which was used to make the prediction of the time of the fade.

**Key words:** galaxies: BL Lacertae objects: individual: OJ 287 – galaxies: quasars: general – black hole physics

## 1. Introduction

The variability of active galactic nuclei has provided means of studying the central engine, its nature and properties. The monitoring campaigns and programs of interesting extragalactic objects have provided extensive light curves to study.

Blazar OJ 287 ($z = 0.306$) has been observed for over 100 years, partly accidentally (Takalo 1994). Since 1993 it has been observed extensively in the OJ-94 project (Takalo 1996) and has been included in many other monitoring campaigns. Similar to other blazars, it shows large and rapid variations in all observed wavelengths and polarization. Usually blazars are considered to be the bright centers of elliptical galaxies, however OJ 287 appears as a point source in optical and radio observations, although there are some indications of an underlying galaxy (Benítez at al. 1996).

The optical light curve of OJ 287 has many features. The most clear ones in the historic light curve from 1890 to 1998 are the quasi-periodic outbursts at about 12 year intervals (Sillanpää et al. 1988, 1996a). More recent observations have revealed a double-peak structure in the outbursts (Sillanpää et al. 1996b, see also Fig. 1). The peaks are not always of the same size in the outbursts, and there is a hint of $\sim 60$ yr period in the size of the peaks.

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There are also numerous other interesting features in the light curve; there are times of fast variations and times of relatively quiescent periods. In winter-spring 1989 the radio flux began a slow descent, and in May the optical flux suddenly dropped to all-time low values (Takalo et al. 1990). The flux returned to normal soon after the deep minimum. This event was different from the reported double-minima (Sillanpää et al. 1988).

There are many models explaining the behavior of OJ 287 (see Sillanpää 1996b for a review). Most of the models involve a supermassive binary black hole in a configuration that produces the 12-year periodic outbursts and the double-peak structure of each major outburst. These models can be divided roughly into two categories: "changes in the alignment of the jet" models and "changes to the accretion rate" models. The former include, e.g., the beaming model by Villata et al. (1998), and the latter, e.g., the tidal interaction model by Sillanpää et al. (1988).

There are few theories explaining the sudden fade of 1989 (Takalo et al. 1990; Kidger et al. 1991). The three suggested mechanisms in Takalo et al. (1990) are: (1) an obscuring dust cloud between us and the central source, (2) a "switching-off" of the central power source, and (3) a temporary misalignment of the jet. All of the mechanisms could produce another fade, and some could even be predicted with a refined model.

Sillanpää et al. (1988) noticed that the light curve of OJ 287 has two different (quasi-) periodic structures: a maximum outburst structure with a period of 11.65 yr and a double minimum structure with a period of 11.05 yr. The interval between the minima was found to be $\sim 1$ yr. The observed maxima were not equally spaced, with up to 0.75 yr difference to the expected time. The aforementioned periodicities led to a model explaining the maxima with a binary system with a 11.65 yr period. The model includes a supermassive black hole binary, where (at least) the more massive component (the primary) has an accretion disk. The smaller component (the companion) moves in the plane of the disk and tidally perturbs the disk during its pericenter passages, causing enhanced inflow to the primary. In this model, the binary orbit has an eccentricity of 0.7. The minima are interpreted as eclipses of part of the disk of the more massive black hole by the accretion disk of the less massive component. The double minimum structure suggests that there are two bright emission regions that are eclipsed in succession. Timescale analyses led to black hole masses of $\sim 5 \times 10^9$ $M_\odot$ and $\sim 2 \times 10^7$ $M_\odot$.

After the 1994 monitoring campaign, it could be seen from the light curve that the outburst structure is actually double-peaked (Sillanpää et al. 1996b). The black hole binary model was unable to produce double peaked outbursts, and Lehto & Valtonen (1996) revised the model to produce two peaks at every pericenter passage. Actually, the new model produces three peaks. The double peaks are the result of the crossing of the accretion disk of the primary by the companion black hole, and the original tidal interaction produces a longer lasting rise of the flux seen as an increase in the base level of the flux. The companion now moves perpendicular to the plane of the accretion disk of the primary. The crossings remove a bubble of matter, which rises from the disk and expands until it becomes too optically thin to be seen in the optical regime. The same tidal action mechanism of the original model still works, when the companion black hole is close to the pericenter. All three emission events at every period take place after a delay; the crossings do not produce radiation until the bubble has emerged from the disk and expanded enough, and the pericenter passing produces tidal instability in the accretion disk, which drives matter into the primary black hole. The crossing delays have been modeled in detail in Lehto & Valtonen (1996). On the basis of their binary black hole model Lehto & Valtonen (1996) suggested that the 1989 fade could be the signature of an eclipse and predicted that the next one would occur at the beginning of 1998.

Pietilä (1998) has studied the possibilities of the Lehto & Valtonen model and other delay options, such as no delay, constant delay, and delay proportional to the infall time. The delay in Lehto & Valtonen depends on the properties of the accretion disk, which is modeled after the Sakimoto & Coroniti (1981) disk model. The crucial parameters of the disk are the viscosity coefficient $\alpha_g$ and the mass accretion rate $\dot{M}$. Pietilä lists limits for the parameters of the binary and the accretion disk, and the future and past events (flares, pericenter passages, and eclipses). The limit for the 1998 fade — interpreted as an eclipse — is $1997.80$–$1998.13$.

New hydrodynamical simulations imply that the crossing of an accretion disk by a black hole produces a fountain on both sides of the disk (Ivanov et al. 1998). This partly solves the asymmetry problem of the crossings in the Lehto & Valtonen model, as the observed outbursts are nearly symmetric (Sillanpää et al. 1996b).

## 2. Observations and data reduction

We have observed OJ 287 using the 2.56 m Nordic Optical Telescope (NOT) at Observatorio del Roque de los Muchachos (La Palma, Canary Islands), the 40 cm Automatic Imaging Telescope (AIT) at the Perugia University Observatory (Perugia, Italy), the 1.5 m Telescope at the Observatorio Astronómico Nacional (San Pedro Mártir, Baja California, México), the 1.05 m REOSC Telescope at the Torino Observatory (Torino, Italy), and the 1.03 m Telescope at the Tuorla Observatory (Piikkiö, Finland). The radio observations were made at the Metsähovi Radio Research Station using the 13.7 m radio telescope. The number of observations obtained at each observatory are listed in Table 1.

### *2.1. Observations at the Nordic Optical Telescope*

#### 2.1.1. Photometric observations

We have made photometric observations of OJ 287 using three different CCD cameras: the StanCam camera, the Andalucia Faint Object Spectrograph (ALFOSC) camera, and the High Resolution Adaptive Camera (HiRAC) camera. The StanCam CCD has a 1k SiTe (TEK1024) chip with 0.176″/pixel and 24$\mu$m pixels. The ALFOSC CCD has a 2k Loral (W11-3AC) chip with

**Table 1.** The number of observations from each observatory from Fall 1993 to Spring 1998.

| **Optical** | **U** | **B** | **V** | **R** | **I** |
|---|---|---|---|---|---|
| NOT | 1 | 1 | 11 | 11 | – |
| Perugia | – | 17 | 456 | 508 | 407 |
| San Pedro Martir | – | 9 | 17 | 16 | 14 |
| Torino | – | 93 | 60 | 141 | – |
| Tuorla | – | – | 132 | – | – |
| **Polarization** | **U** | **B** | **V** | **R** | **I** |
| NOT polarization | 2 | 2 | 2 | 1 | 1 |
| **Radio** | **22 GHz** | | **37 GHz** | | |
| Metsähovi | 140 | | 122 | | |

0.189″/pixel and 15 $\mu$m pixels. The HiRAC CCD has a 2k Loral (W14-2AC) chip with 0.110″/pixel and 15 $\mu$m pixels.

Most of the observations have been made using UBVRI filters with standard Johnson/Kron-Cousins responses. Some observations (27 February 1998, NOT) have been made with Gunn R filter, because the Kron-Cousins R filter was temporarily unavailable. The CCD frames were reduced (de-biased and flat-fielded) using standard techniques with the IRAF-package; the magnitudes were determined from relative photometry using the standards by Smith et al. (1985). In most cases we used star 10 as the comparison star, but sometimes it was saturated so we used star 11 instead (Smith et al. 1985). The integration times varied from 30 to 120 seconds. We invited observers at the NOT telescope to monitor OJ 287 during January and February 1998, in addition to our three observing runs.

#### 2.1.2. Polarimetric observations

The polarization measurements were made using the Turku photopolarimeter (5 January 1998) and the ALFOSC CCD camera (20 January 1998).

The Turku photopolarimeter is a double beam chopping photopolarimeter that uses four dichroic mirrors and five photomultipliers to achieve simultaneous measurements in the UBVRI bands. The filters give Johnson (UBV) and Kron-Cousins (RI) responses. A more detailed description of the instrument can be found in Korhonen et al. (1984), and the observation and data reduction methods have been described in Takalo et al. (1992).

We made a total of 32 single observations with a 10 s integration time (for each of the eight positions of the calcite crystal). This gives us a total of 43 min of observation time of OJ 287. The observations were averaged due to poor conditions. The R and I channels were unavailable during our observations.

With the ALFOSC CCD camera, we used imaging polarizing optics consisting of a calcite crystal and a half-wave retarder plate to get two images of the object on the same frame. We used the calcite crystal in $0°$ and $45°$ orientations to obtain two of the normalized Stokes parameters (Q/I and U/I) using differential photometry, and from them we calculated the degree of linear polarization and the polarization position angle. The CCD frames were reduced using standard reduction techniques with the IRAF package. The filters used were the same as in the photometric observations. The integration times varied from 60 to 300 s depending on the band.

We have also observed zero and high polarization standard stars to correct for instrumental polarization and to get the zero point correction for the polarization position angle (Schmidt et al. 1992).

### *2.2. Observations at the Perugia Observatory*

The Perugia photometric observations were carried out with the 0.4 m Automatic Imaging Telescope (AIT) (Tosti et al. 1996). The integration times during the exposures varied from 4 to 6 min depending on the brightness of the object. Data reduction was performed with locally-developed software packages, which apply all the standard corrections required (bias and dark subtraction, flat field correction) and the instrumental magnitudes computation. The $R_c$ magnitudes of the comparison stars in the field of OJ 287 have been published by Fiorucci & Tosti (1996).

### *2.3. Observations at San Pedro Martir (SPM)*

Observations were carried out from January 26 to 31 (UT) with the 1.5m (f13.5) Telescope at SPM. The detector was a Tektronix TK1024AB CCD. This chip has $1024 \times 1024$ pixels, each $24.5 \times 24.5$ $\mu$m, (the scale of plate of the system is $\sim 0.25''$/pix).

Broad band B,V (Johnson) and R,I (Cousins) filters were used in this run. The reductions were made using IRAF in the standard way (bias subtraction, flat-fielding and cosmic ray correction). The photometry was done using IRAF/APPHOT with an aperture of $2''$. Details will be found in Dultzin-Hacyan et al. (1999).

### *2.4. Observations at the Torino Observatory*

The observations were made with the 1.05 m REOSC telescope equipped with a $1242 \times 1152$ pixel CCD camera with a $\sim 0.47''$ per pixel scale. Standard BV (Johnson) and R (Cousins) filters were used with integration times varying from 240 to 420 s depending on the band. Data were reduced by using the locally-developed Robin procedure, including bias subtraction, flat field correction and circular Gaussian fit after background subtraction. For more details see Villata et al. (1997).

### *2.5. Observations at the Tuorla Observatory*

The observations were made using the 1.03 m telescope at the Tuorla Observatory equipped with a $1530 \times 1020$ pixels ST-8 CCD camera. Only a V filter with standard Johnson response was used. For more details, see Katajainen et al. (in preparation).

### *2.6. Observations at the Metsähovi Radio Research Station*

The radio observations were made at the Metsähovi Radio Research Station, as part of an ongoing long-term project to

**Table 2.** The polarization observations made at the NOT. $P$ is the polarization degree and $\theta$ is the polarization position angle.

| Date / Instrument | | U | B | V | R | I |
|---|---|---|---|---|---|---|
| 5 Jan 1998 | $P$ [%] | $12.6 \pm 1.6$ | $10.4 \pm 1.4$ | $10.6 \pm 1.4$ | – | – |
| *TurPol* | $\theta$ [°] | $136.2 \pm 3.6$ | $137.9 \pm 3.7$ | $138.9 \pm 3.7$ | – | – |
| 21 Jan 1998 | $P$ [%] | $13.2 \pm 1.0$ | $14.5 \pm 0.5$ | $12.3 \pm 0.5$ | $12.8 \pm 0.4$ | $10.8 \pm 0.8$ |
| *ALFOSC* | $\theta$ [°] | $1.6 \pm 2.0$ | $2.5 \pm 0.8$ | $1.9 \pm 1.1$ | $-4.8 \pm 0.8$ | $-0.3 \pm 0.8$ |

monitor extragalactic radio sources. The monitoring started in 1980 and now includes over 80 sources, which are mostly flat-spectrum northern sources. The observations have been made at two frequencies, 22 and 37 GHz, using a dual-beam method on the 13.7 m Metsähovi Radio Telescope. The fluxes are relative fluxes calibrated against DR21 according to the flux-scales in Baars et al. (1977). The data presented here are weekly averages. The observational techniques are described in more detail in Teräsranta et al. (1992).

## 3. Results

We have good coverage at the R and V bands and fair at I band. There are some observations in the B band and only one in the U band. The radio observations cover the time-span pretty well except for the critical February 1998. Fig. 1 shows all the optical observations in the V, R, and I bands since Fall 1993; in the V band figure we have included the published data from the OJ-94 project (Sillanpää et al. 1996a, 1996b). The lower part of the figure shows the historical light curve before the 1989 fade in the V band. Fig. 2 has radio observations from the same epochs as Fig. 1 in 22 and 37 GHz. The areas around the 1989 and the 1998 minima have been expanded to Fig. 3 and Fig. 4. The polarization data have been listed in Table 2.

There have been two major outbursts in the optical every decade for the last 30 yr. The last six outbursts have peaked at 1971.87 (37 mJy, 12.5 mag), 1973.00 (21 mJy, 13.1 mag), 1983.02 (22 mJy, 13.1 mag), 1984.18 (11 mJy, 13.8 mag), 1994.85 (10 mJy, 13.9 mag), and 1995.98 (11 mJy, 13.8 mag) with the peak flux and magnitude in the V band in parentheses (Sillanpää et al. 1996a, 1996b). The two peaks in the eighties are before the beginning of the lowest panel in Fig. 1. The height of the peaks has decreased in these outbursts, but looking at the historic light curve since 1890 gives an impression of an oscillating feature in the power of the outbursts; there is hint of a $\sim 60$ yr period (Sillanpää et al. 1996b). The two latest outbursts can be seen in Fig 1. They are somewhat symmetric about the point 1995.4 (Sillanpää et al. 1996b). The colors of OJ 287 are usually very stable even during the outbursts, which can be seen in comparisons of the simultaneous V,R, and I data in Fig. 1. There is lot of smaller $\lesssim 0.5$ mag variation around the base level, which stays quite high after the second outburst and decreases slowly until the end of 1997.

In the later half of the eighties there were no major outbursts. In 1985 the brightness rose up to 14.5 mag, but after that it stayed around 15.5 mag with $\sim 0.5$ mag variations. In the end of 1988 the variations increased and the brightness went up to $\sim 14.6$ mag. There were two sharp peaks before it started to fade.

The radio data from the two epochs are completely different (see Fig. 1). Since 1993 there was only one outburst; this was almost simultaneous with the optical outburst peaking at $\sim 1995.9$. The maximum flux level was $\sim 4$ Jy in both wavelengths. After that outburst OJ 287 has been extremely quiet. The flux has steadily been increasing from $\sim 1.5$ to $\sim 2.5$ Jy, with almost no short-term fluctuations. In the late eighties, the flux level was $\sim 6$ Jy, but the variations were much more violent as the flux varied from $\sim 2$ to $\sim 10$ Jy, as seen in Fig. 2.

If we look more closely at the minimum of early 1998 in Fig. 3, we see that the brightness had started to decline in December 1997. The decline is fairly linear and steady, and can be seen in all optical bands that have enough data. In the beginning of February 1998, the magnitude reached $\sim 16.2$ mag, when it suddenly rises by $\sim 0.5$ mag and then comes down to its previous level in about a week. This rise can be seen in the V, R, and I plots, but the other bands lack data from the same period. The sharp peak before the minimum is simultaneous in all available bands. The V and R data show that the brightness could have dropped even more after the sharp rise; the minimum values have large errorbars compared to other points. The time of the deep minimum of R=$16.34 \pm 0.10$ and V=$16.91 \pm 0.13$ mag was $\sim 1998.14$ in both bands.

The 1989 data shows a fade that is much deeper than the fade in 1998 (see Fig. 3). The magnitudes of the deepest minima were R=16.63 mag and V=17.40 mag, $\sim 0.5$ mag less than in 1998. The minima were not exactly simultaneous in all bands. The V minimum was at 1989.38. There is some similarity in the two fades. Although the time coverage of the data is not as good as ours, the B,V, and R band data seem to show that there is also a sharp $\sim 0.6$ mag peak before the minima. These peaks are also exactly simultaneous. The I band data is different from the other bands, but the minimum might have been misclassified and interpreted to precede the other minima by a week. If one identifies the I band minimum with the local minimum before the peak, then they are simultaneous.

The degree of polarization of OJ 287 at optical wavelengths has increased from $\sim 5\%$ in 1993 to $\sim 20\%$ in 1997 with highs over $30\%$ (Efimov & Shakhovskoy 1997). At the same time, the position angle was seen to rotate counter-clockwise $\sim -5°/$day in 1993–1996 (Efimov & Shakhovskoy 1996), which changed to nonlinear variability between $\sim 145°$ and $\sim 185°$ in 1996–1997 (Efimov & Shakhovskoy 1997). The latest values in spring 1997 were $\sim 28\%$ and $\sim 160°$. Our observations are listed in Table 2. The degree of polarization is lower than the

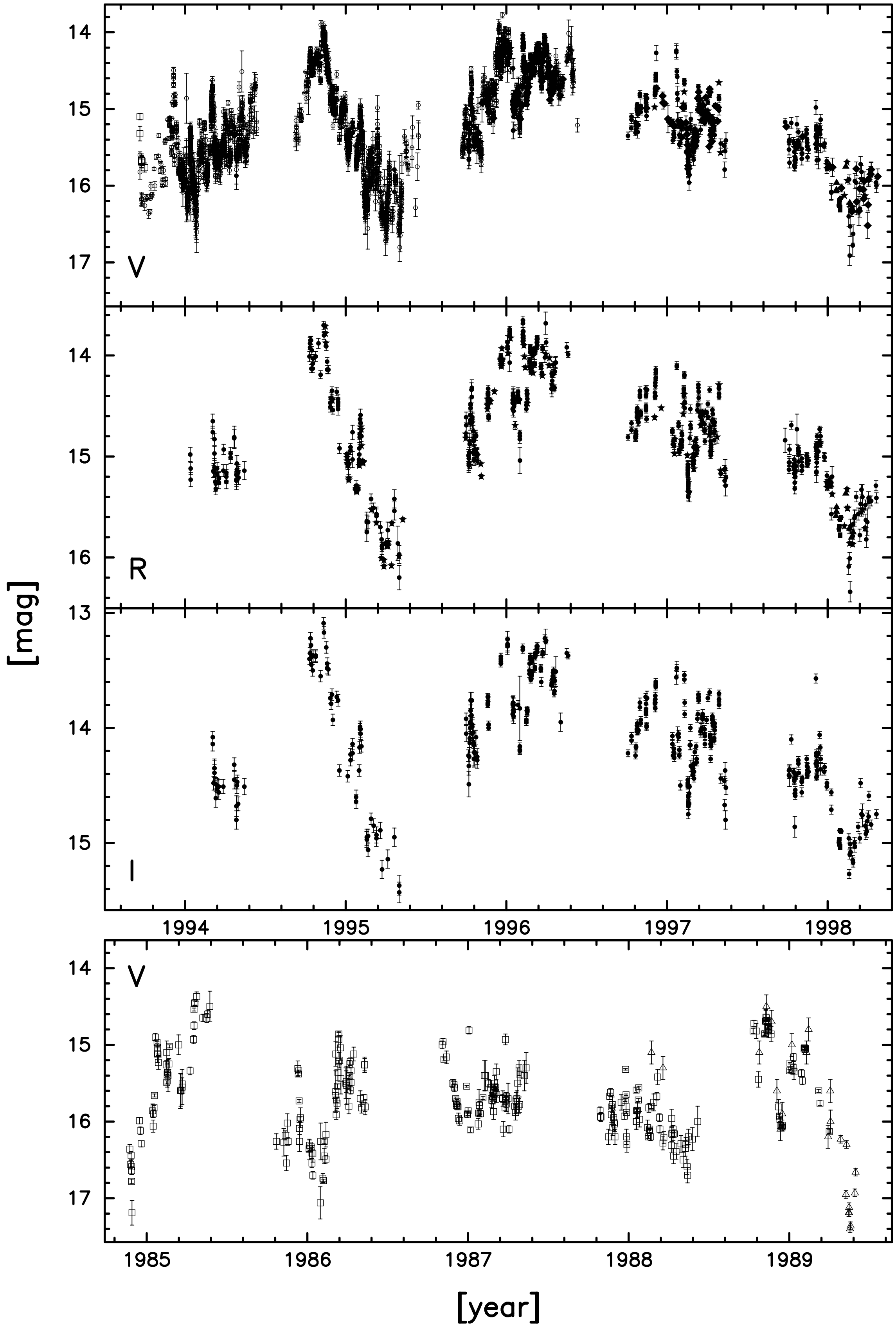


**Fig. 1.** The upper 3 panels show optical observations of OJ 287 from Fall 1993 to Spring 1998 in the VRI bands. The lowest panel shows the historical V band light curve and the 1989 fade points from Fall 1984 to Spring 1989.

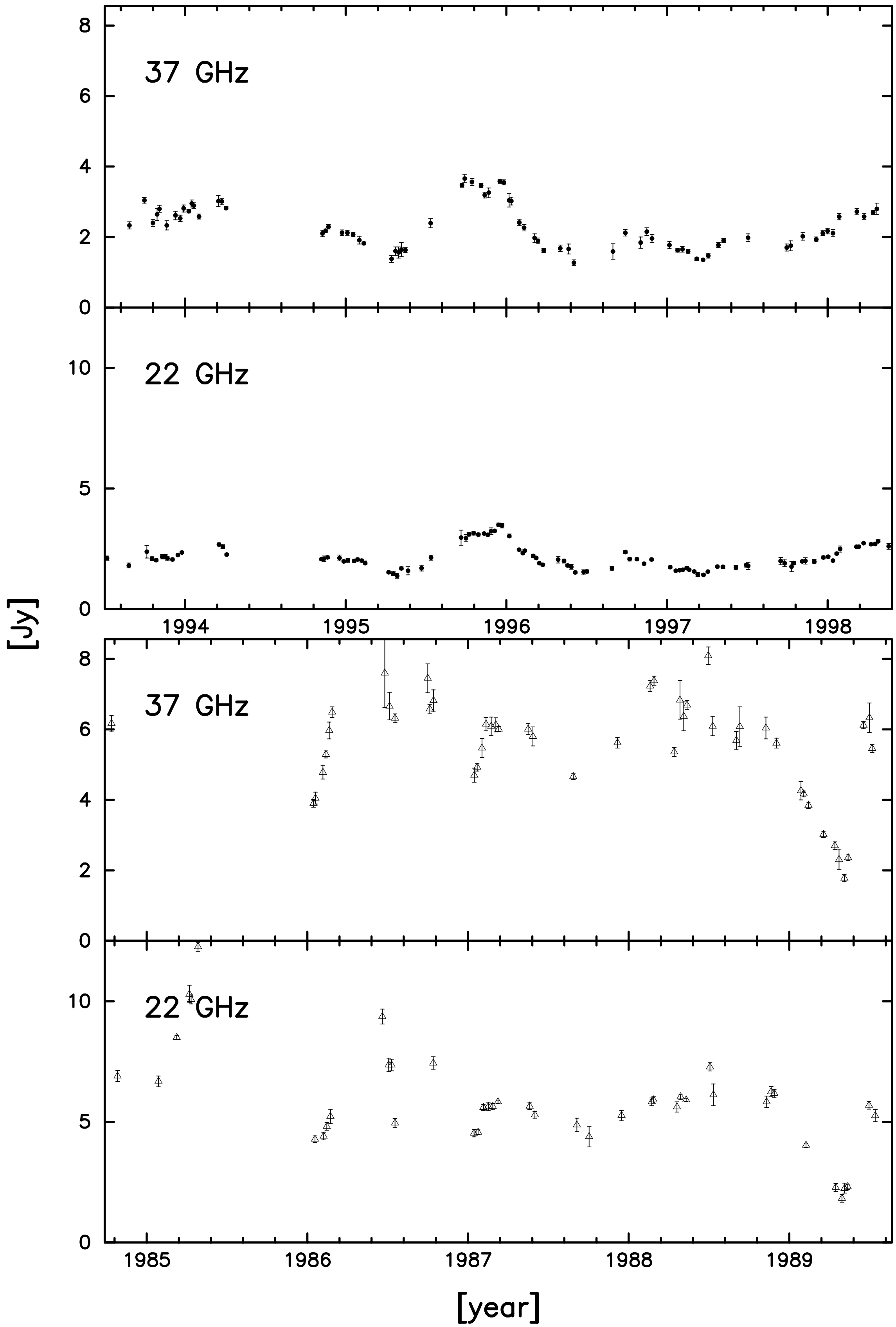


**Fig. 2.** The upper part shows the radio observations of OJ 287 from Fall 1993 to Spring 1998 and the lower part shows the radio observations from Fall 1984 to Spring 1989 in the 22 and 37 GHz bands.

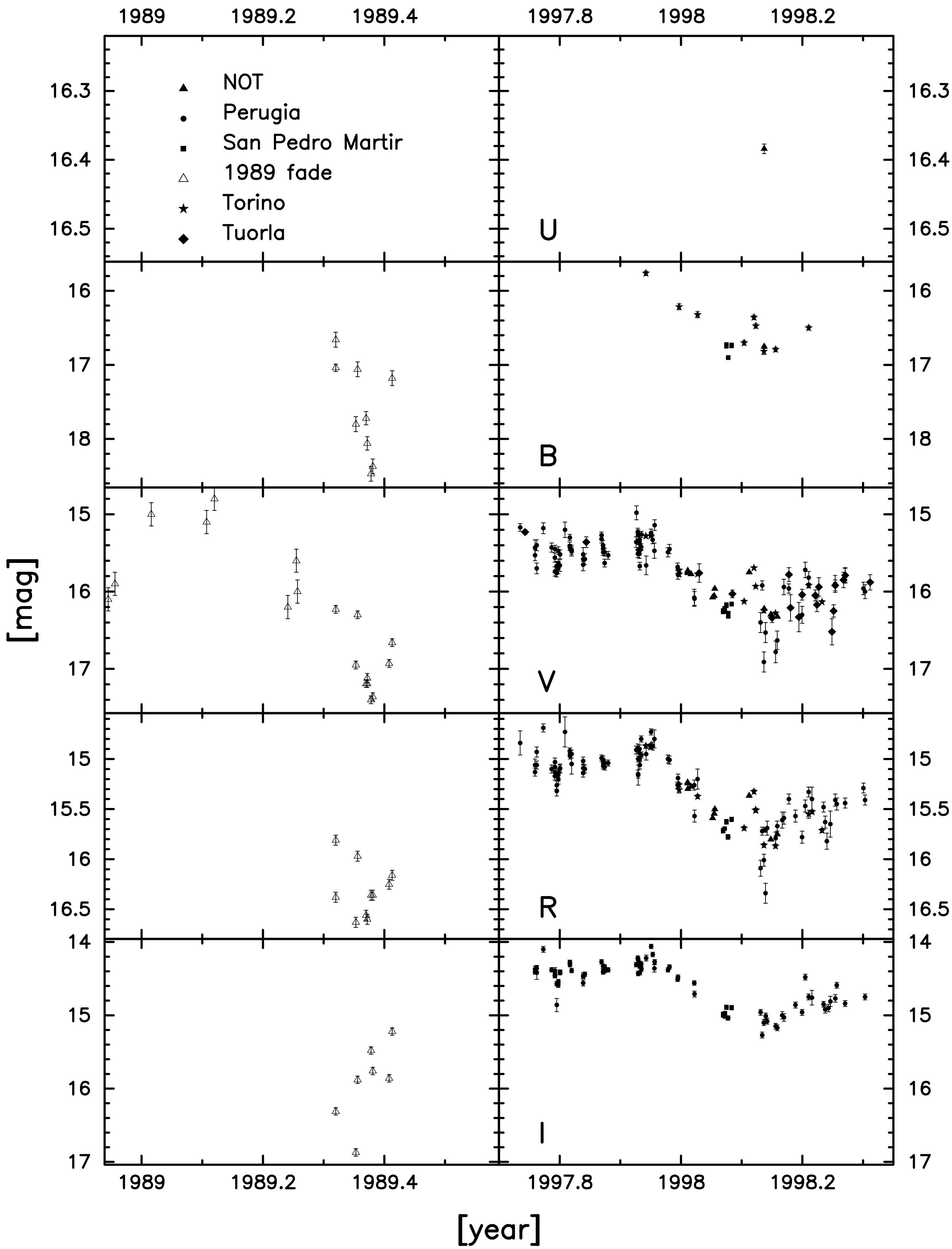


**Fig. 3.** Optical observations of OJ 287 during the 1989 fade (Takalo et al. 1990) and from campaign in the UBRVI bands.

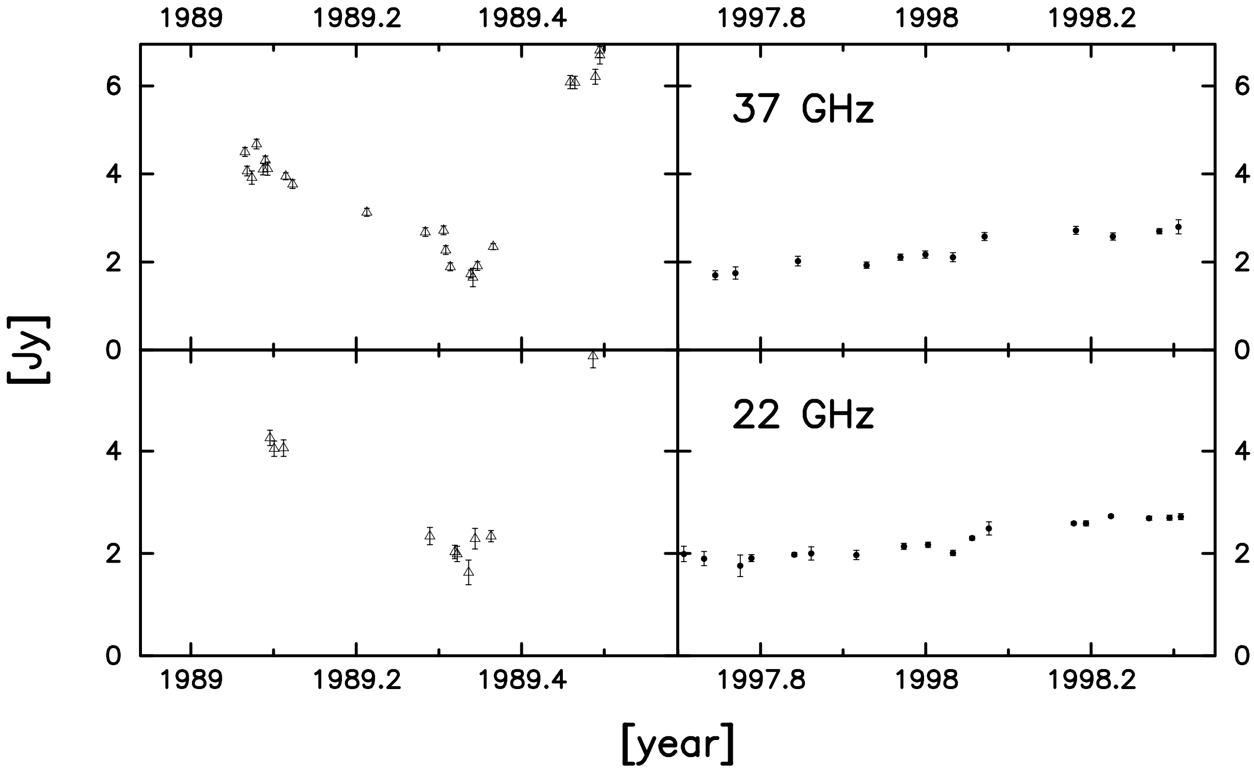


**Fig. 4.** Radio observations of OJ 287 during the 1989 fade (Takalo et al. 1990) and from campaign in 22 and 37 GHz.

trend in 1993–1997 would have predicted, but there have been quite large variations before and $\sim 13\%$ is a very typical value for OJ 287. The polarization angle changed about $45^\circ$ in the 16 days, which is somewhat slower than the linear trend of change of polarization angle in 1993–1996, and the values are similar to the ones in 1996–1997.

## 4. Implications for the models

There are several observational aspects of the fades that models have to explain:

1. The 1989 fade is much deeper than the 1998 fade and it also lasted longer.
2. The 1998 fade showed a sharp peak, which might be present in the 1989 data too.
3. In 1998 the decline before the minimum was very steady, but the incline after the sharp peak and the deeper minimum was very variable.
4. The radio fade in 1989 started much earlier than the optical one and there was no radio fade seen in 1998.

Some of these features are probably connected, e.g., the missing 1998 radio fade is most probably connected to the low flux level since 1996.

Could we explain the 1998 observations, and the reoccurence patterns in the context of the possible scenarios presented by Takalo et al. (1990)? The obscuring dust cloud theory would have to presume a series of clouds with just the right properties to get the observed light curves in optical and radio. A binary black hole could achieve the variations by distorting the accretion disk of the primary in a "switching-off" model. The jet could also be misaligned in a way to produce the observed features. But all these suggestions lack a detailed model that gives quantitative answers and they do not address the missing radio fade. The binary black hole models do however explain the reoccurence.

In the binary black hole model by Lehto & Valtonen (1996) the companion is thought to be at such a high inclination that it goes very close to the jet. As the radio emission regions in the jet are thought to be further in the jet than the optical regions, the companion could travel between the two regions which could explain why there was no radio fade in 1998 (Valtonen et al. 1999). The reason for this is that the 1989 fade, or the eclipse according to the model, happened very close to the apocenter, but in 1998 the orbit has precessed so much that the eclipse occurs closer to the primary black hole. When the companion approaches the jet of the primary black hole, it must have an effect on the direction and other properties of the jet. The slow approach could cause the observed steady decline, which ends when the companion is too close to the jet. Then the jet changes direction rapidly and at some stage points towards us causing the sharp peak. Then the accretion disk of the companion blocks the optical emission region, which is seen as the deep minimum. The radio emission is unaffected, because the radio emission region is further from the primary than the companion (Valtonen et al. 1999). The companion leaves the jet in tangled manner, which could be seen as the variations after the minimum and it should also affect the degree of polarization. Our polarization data does

**Table 3.** The range of parameters for acceptable solution in the Lehto & Valtonen (1996) model.

| Parameter | Mean | Range |
|---|---|---|
| Primary mass [$10^{10}$ $M_\odot$] | $1.49$ | $1.483$–$1.497$ |
| Companion mass [$10^{8}$ $M_\odot$] | $0.93$ | $0.882$–$0.978$ |
| Semi-major axis [pc] | $0.051$ | $0.0511$–$0.0512$ |
| Eccentricity | $0.668$ | $0.6672$–$0.6685$ |
| Viscosity coefficient | $0.37$ | $0.250$–$0.890$ |
| Mass accretion rate [$\dot{M}_{\rm edd}$] | $0.02$ | $0.003$–$0.033$ |

not cover that period. After the minimum, the flux of OJ 287 should gradually stabilize. As the companion is still moving away from the primary black hole, the brightness of OJ 287 should stay at low values for some years. The next predicted crossing of the disk in 2006 occurs far in the disk and should not produce large flares (Pietilä 1998).

Pietilä (1998) has studied the parameter space of the Lehto & Valtonen (1996) model. The implications of the timing of the 1998 fade for the range of acceptable parameters can be found by looking at those solutions that have the required eclipse time. The solutions that have an eclipse time between $1998.12$–$1998.14$ are presented in Table 3. The parameters can vary in a narrower range, but they are similar to the original values of Pietilä (1998). The only bigger difference is in the range of the mass accretion rate. Without the restriction above, the mass accretion rate $\dot{M}$ was not much limited; the range was $\dot{M} = 0.002 - 0.901$. But the late eclipse time seems to favor only those solutions that have very small accretion rates: $\dot{M} = 0.003 - 0.033$. This eclipse time also rules out small viscosity coefficients: $\alpha_g = 0.25$–$0.89$.

## 5. Conclusions

The time of the lowest brightness of OJ 287 since 1995 is within the limits of the prediction of the time of the 1998 (Pietilä 1998). The observations show a sharp peak and subsequent fade at $\sim 1998.139$, which is seen on R,V, and I bands. The others lack data from the same time period. Only R and V band data show the deep minimum (with large errorbars), and also the I band minimum is the lowest magnitude since 1995. If the points with large errorbars are removed, the minima, in all the bands B, V, R, and I, still show the lowest brightness of OJ 287 since 1995.

We do not have the exact answer to what caused the 1998 minimum, but the coincidence of the time of the minimum with the prediction of the Lehto & Valtonen (1996) model shows that the suggestion of the binary black hole system is probably relevant, although the details of the various mechanisms remain to be clarified.

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